

be considered during the formulation of the program and not later when the program structure is in place and the program is in progress. Change is almost always costly; requirements traceability provides a bulwark against which the program manager and the systems engineer can stand and defend.

Baseline Cost, Schedule and Performance

The three main parameters in the control process—cost, schedule and performance—are the program manager's bread and butter. Again, program definition is vital and necessary from the very beginning. It may be argued that clear definition is not possible, particularly early in the program; nevertheless, an approved, traceable baseline, although it may alter, must be known at any given time, and must include everything in the program. The "I forgot" can kill you. The key to success in handling these three parameters is to manage the balancing act between them. Cost, schedule and performance are usually dependent variables and at various times, one or another may assume greater or lesser importance. A single variable, however, should never be changed without knowing the impact on the other two. Within the NASA culture, performance is generally the predominant factor, and schedule is a distant second. Cost tends to be considered mostly in the context of the annual appropriation, but from the point of view of the program manager, all three parameters must be defined and approved continuously, which is a function of the systems engineering process.

Program Risk Analysis

In recent years, especially since the Challenger accident, program risk analysis has come to be used largely in the context of crew safety, but this is only a part of program risk. Basically, program risk analysis assesses the probability of meeting requirements as changes occur. A number of analytical tools now available can be used to under-

stand the relationships between cost, performance and schedule. Again, a small group within the systems engineering organization should be dedicated to understanding the impact of any change on all three parameters. Armed with this information, risk can be reduced in many ways. Adding more money, reducing the performance requirements, or extending the schedule are most often used. A competent systems engineer will know the relationships between these three variables and the impact of any situation on the total program.

The Role of Cost in Phased Procurement

The most common form of procuring high technology capability within the Federal Government is known as phased procurement. The theory behind this procurement method is that commitment to the program gradually increases with time and in discrete stages. Within NASA, there are four standard phases; others are beginning to creep in as the ability to establish new programs becomes more difficult and the duration and cost of operations becomes a more significant part of total program costs. The role of cost is different in each of the phases. The phases are:

Pre-Phase A: This is a very unstructured period that examines new ideas, usually without central control and mostly oriented toward small studies. This period can last for a decade or more and produces the list of ideas and alternatives from which new programs are selected.

Phase A: Sometimes called the feasibility phase, this is a structured version of the previous phase. Usually a task force or program office is established, and multiple contracts will be awarded. The goal of this phase, which may last for several years but usually is limited to one or two years, is to decide whether a new program will be started and what its purpose and content should be. This phase repre-

sents less than one percent of the total program costs. Nevertheless, it is largely a systems engineering effort and sets the stage for everything that follows.

Phase B: Sometimes known as program definition, this phase is the most important in establishing the basic parameters of the program. By the time this phase is finished (a period of two or three years), the program rationale, cost, schedule, performance, management style and the most likely technical solution will have been established. This phase usually involves multiple contracts to establish a variety of ideas and a competitive environment, should the program proceed. Cost is continuously assessed as a function of design solutions relative to basic requirements. Studies indicate that from five to ten percent of the total program costs will need to be expended if control is to be maintained over the program during Phases C and D.

Phase C/D: Originally separate phases, this period covers design, development, test and evaluation. Contracts may be open to all qualified bidders or only to those involved in the previous phase. Although competition is not usually open between Phases C and D, commitment to Phase D depends on a successful and acceptable design. In past programs, two-thirds of the total program cost was expended during this period. The systems engineering role has begun to shift toward systems specification and systems interfaces. The secret to cost control is a sound definition of end items and their interfaces with a tight hold on changes.

Phase E: In most past programs, the operations costs were less than 20 percent of the total cost. This was because there was a definite end to a relatively short-term program. In recent years, particularly in the manned programs, the length of the

operational phase has increased significantly. In the case of the Shuttle, it could be conceived as indefinitely long. For this reason, life cycle costs should be a major consideration from the beginning.

Selling the Program

The definition of a new start within NASA varies by program and organization but can generally be said to occur at the beginning of Phase B. Prior to that time, the program manager is selling the program. The total expenditure of funds during the selling period is usually far less than one percent of the final program costs; this is, however, when the basic parameters of the program are established. It is a time of building constituents both inside and outside the Agency. Assuming that a feasible technical solution is available and an acceptable management scheme can be provided, much of the debate about whether a program should be approved centers largely around the question of cost. Of course, with only preliminary designs available, only cost estimates can be made and these are obtained from standard cost models.

Cost Estimating

During Phase A of the program, when the most rudimentary designs are available, it is essential that program cost estimates are made before the program start can be authorized. Estimates are made using cost models that have been developed on the basis of past experience on similar programs. These models are among the most arcane devices invented by engineers, so a few words on how they work are appropriate.

Past experience is captured by documenting the cost of each system on the basis of weight. Regression analysis is performed to determine a straight line log relationship. Once the weight of the system has been estimated, the cost can be determined. This estimate is multiplied by a complexity factor to allow for the risk associated with the select-

ed technology and may vary from as little as 0.50 to 2 or more. This is repeated for each system, and the total becomes the baseline cost. This total is multiplied by a factor to allow for systems engineering and testing by the prime contractor. This is known as the "prime wrap" factor and is again determined based on all relevant past experience.

All prime contractor estimates are added and then multiplied by a second factor known as the "nonprime wrap." This is the cost of government work. Finally, a reserve factor is used to allow for problems during the program. There are separate cost models for manned and unmanned programs, which are significantly different. In general, for the unmanned programs, about 40 cents of every dollar goes to hardware, and in the manned programs, about 20 cents.

These cost models pose a great many problems. First, they are normalized on the basis of weight. Clearly this is not valid in all cases, particularly structure. Second, they do not explain why the costs are what they are. Factors such as management style, procurement strategy and test philosophy are not differentiated. Third, they include all past experience, including errors and overruns. In this respect, these cost models assume no learning curve. As it was in the beginning, is now, and forever shall be! They must therefore be used with great caution. From the systems engineer's point of view, these cost models can be used to assess the relative costs of various design solutions; on an absolute basis, however, they are of little use.

So far we have been able to make a tentative estimate of the cost of the flight system. To this must be added the cost of new facilities, including launch, test beds, flight operations, networks and data reduction, among others, and finally the cost of operations. It is at this point that the program manager faces

the first dilemma: What should be included in the program cost? That sounds like a simple question, but it is complicated by the fact that not all costs are under the control of the program manager, nor is he or she responsible for justifying all of the associated appropriations.

For example, launch costs are provided by the Office of Space Flight, network costs are provided by the Office of Operations, and civil service costs are provided by the research and program management fund managed by the Office of the Comptroller. New buildings are provided under the construction of facilities budget. In addition, most new program managers are surprised to find that a tax based on the number of civil servants working on the program varies from Center to Center, and neither the number of people nor the level of tax is under the control of the program manager. Taxation without representation! Despite this dilemma, the systems engineer should include all of these factors in the cost estimate because the chosen design will affect all of them; overall program costs are as important to the Agency as direct program costs.

Program costs tend to be presented as only those costs that are under the control of the program manager. No matter how much this limitation is stated in presentations, it is assumed that it is the total program cost (especially when it is a popular program) that has the support of the Executive branch, the Congress and other constituencies. It is no wonder that the average program increases in cost by a factor of about three from the time of approval to completion and that most program managers during this period are accused of everything from naiveté to self-deception to outright lies. There is the added ethical question that if all costs were actually presented, the program would not be approved!

Defining the Program

This phase of the program, usually known as Phase B, will take from one to two years. The purpose is to take the various concepts considered in Phase A and select a single valid solution. By the time Phase B is over, a clear set of requirements should be available with a complete set of functional specifications and a cost estimate based on preliminary design concepts rather than on cost models. These are primarily produced by the systems engineering organization and include at least one preliminary design and selected technologies with well-understood risks associated with those technologies.

Don Hearth, former director of the NASA Langley Research Center, performed a study on how much this phase has cost for various past programs as compared to the success of the program in later phases. Success was measured as the ability to maintain performance, schedule and cost as determined at the end of Phase B. He concluded that the most successful programs spent between five and ten percent of the total program cost in Phase B. The scope was limited to unmanned programs, but the rationale can reasonably be extended to manned programs.

Apart from establishing a credible functional system specification, it is essential to determine the management structure, the procurement strategy and a baseline cost for the life of the program, including the cost of operations. Once again, the primary method for cost estimating is the cost model, but there should be sufficient detail available to check the model with bottom-up costs based on feasible design solutions. The systems engineer is responsible for comparing these two cost estimating techniques. It is unwise to proceed to the next phases unless some bottom-up cost estimating has been performed.

Perhaps the most important product of this phase is a complete work breakdown struc-

ture. Again, this is largely the responsibility of the systems engineering organization. The axiom to be followed is, "You cannot control what you have not defined."

Work Breakdown Structure

Too often a program will be approved without a well-established work breakdown structure (WBS) describing the whole program, which inevitably results in large cost overruns. The WBS is the basis for the procurement strategy and often for the management structure. Without it, program changes will take place after the contractors are in place and have to be paid. Overlaps between contracts, as well as missing elements and contract changes, are always expensive. The following simple rules have to be followed:

1. Each element of the WBS should contain a deliverable that can be defined.
2. The sum of the WBS elements must be the total program. (Note that a given program manager may not have the responsibility for all elements, but they should each be defined and allocated.)
3. Each deliverable should be accompanied by a cost and a schedule. The cost should include a reserve based on the estimated risk associated with that element, and the cost should be allocated to that element.

As simple as these rules sound and as much as NASA requires contractors to adhere to them, the internal track record is dismal. We can go a long way toward containing costs if discipline is established early and maintained.

One last word of caution. A WBS element should never be established on the basis of function or organization. These elements are not end items. Other mechanisms exist for identifying these elements, which in general

could be defined as program overhead and not entirely the responsibility of the program manager. They should be recognized for what they are and identified, but they should not be included in the WBS.

Managing the Program

We have now reached the time in the program when promises have been made, deals have been struck, and the program has been approved. All that remains is to deliver. A custom within NASA stipulates that new managers are instilled with the belief that the skills required to sell a program and to define it are different than those required to run it. Certainly some changes can be expected, but I believe that such changes are better if they occur sometime after a phase has been entered and the basic management structures have been established. What the program needs at this time is ownership of the concept, and changes in management will usually result in program changes that inevitably will lead to increased costs. This is particularly true of the systems engineering group that has carefully balanced the requirements against the design and is familiar with the "why" of a decision as well as the "what." So far the total expenditure has been relatively low, but once the contractors are onboard and the manpower begins to build up, costs can escalate at an alarming rate. In a very short time, increases or decreases in performance, extensions or reductions in schedule, and decreases in annual funding will all increase cost.

Design to Cost. There is much talk about design to cost but very little action, and for this there are a number of reasons. Earlier, I mentioned that within NASA there is a tendency to order the three variables by performance first, schedule second, and only then worry about cost. So by tradition, cost tends to be put on the back burner. One of the reasons for this is that during the Apollo program, the cost function was transferred to the budget and program control groups. In a

program where the technical problems were so difficult and the budgets were ample, this was understandable, but this is no longer the case. This situation resulted in a shift away from making the design engineer accountable for cost as well as performance and schedule.

The second problem occurs when the cost is not allocated at the WBS element level, where it can readily be traded against performance and schedule and easily traced. I believe that cost must be allocated to the lowest possible level (a little scary for the program manager), but unless this is done, it will be impossible to hold the designer accountable and unlikely that overall costs will be held in check.

The third problem is that in an organization that prides itself on technical excellence, it is very difficult not to make things a little better; consequently, there are always plenty of ideas around. The credo of the systems engineer should therefore be: "The better is the enemy of the good."

Design to Life Cycle Cost. Over the past decade, the operational costs of NASA programs have steadily risen as a percentage of total program costs, largely due to the fact that programs have a longer life in the operational phase. Whereas 20 years ago operational costs amounted to no more than 20 percent of costs, they are now approaching half of the NASA budget. It is time to place design to life cycle cost on an equal footing with design to cost. The dilemma is that a design that allows low-cost operations will usually demand higher development costs and in turn, this means larger front-end program costs. It is essential that the systems engineer make these assessments. The simplest thing for a program manager to do is walk away from this dilemma and let the operations people worry about it later. As this is becoming an overall problem for the Agency, the ability to make new starts will de-

pend on the ability to ensure that a sufficient percentage of the budget is available for operations.

Unfortunately, it is difficult to get enough operations people to participate early in the program, but I believe it is essential. Some kind of veto power should be established when it comes to making design decisions; too many program managers do not feel responsible for operations costs and perhaps, what is worse, are not held accountable for it. Let there be no doubt that operational costs are unacceptably high. An operational concept must therefore be developed early enough in the program to have an effect on the design process.

Change Control. Once a program is underway, the program manager's responsibility is controlling change, which is inevitable. Earlier I said that you cannot control what you have not defined. It is equally true that you cannot control changing something that is not defined. First know what it is! A complete WBS with allocated schedule and cost is, once again, the key. Change requests must not be limited to solving a technical problem. They must be accompanied by cost and schedule impacts and, just as important, life cycle cost impacts.

In addition, there is always a rippling cost impact caused by change. Other WBS elements may be affected, including items in different contracts or in totally different NASA codes, or line items. For these reasons, change must be assessed at the systems engineering level as well as at the WBS level. Perhaps the overriding rule is that changes should be difficult to approve but easy to implement once the decision is made.

Managing Cost Reserves. A qualified cost estimator would not let a program get started without making provision for cost overruns or reserve. The many uncertainties in a development program make it essential. An

analysis of past programs allows a fairly accurate estimate to be made of what is a reasonable total amount as a percentage of total costs, assuming that the programs are similar. Determining how and when the allowance should be allocated is much more difficult. One school of thought says that reserves should be held at the highest level in the program and applied only to correct unforeseen occurrences. The problem is that this tends to bail out poor performers.

I believe that the reserve should be determined based on the perceived risk of the element when the WBS is formulated. The manager of the element should then be held responsible for the stewardship of the reserve. In order for this to work, some sort of reward system must be established for the manager who does not spend the reserve. In any case, it would be prudent to maintain some reserve at the central level for those things that cannot be anticipated. Just to keep the system honest, a very simple tracking program can be established to follow the expenditure of the reserves at the WBS element level after the fact. I would like to see an indepth study done on this subject.

Traps and Pitfalls

So far we have talked about where cost fits into the program management and systems engineering processes. There are a few areas that may catch the program manager unprepared and a few ideas that may be used to make life a little easier in the future. It may not be possible to implement all of them, but it is worth a try.

Buying In. If you are involved in the selling of the program, the easiest trap to fall into is underpricing the program. Despite stories to the contrary, I do not believe that this is a matter of deliberate low bidding. Although I once heard a distinguished gentleman say that we do business the old fashioned way, we do underbid and make up on change requests. The fact is that every program man-

ager I have ever met was convinced that he or she could do it for less than the past record would suggest. Unfortunately, this usually involves changing the way we do business. I believe that there are less expensive ways, but you should tackle this one at your own risk and only if you have the support of the very top of the organization. The systems engineer must be the conscience of the program manager during this period.

Design to Budget. Let us assume that we have completed a perfect Phase B and that everything is in place, including the rate of expenditure by year. It is a virtually certain that two things will happen. First, with eloquent rationales and spreadsheets by the ton, the various element managers will find a need to increase their funding allocation. One favorite argument will be that the sellers of the program, who are no longer in charge, will be blamed for not understanding the problem. In addition, Congress may add a requirement or two.

Second, the budget will be cut in the Agency, at the Office of Management and Budget, and finally in Congress. At this point, the intricate patterns of dependency between performance, cost and schedule begin to unravel. In the first year, this is not devastating because you can always delay bringing the prime contractors on board. But by the time they arrive, the trap has been set for the most insidious form of management, design to budget. Unfortunately, a fact of life is that very few research and development programs have multi-year funding, and annual budgets will be less than planned. The net effect is that program costs will escalate, and enormous pressures will attempt to bring down the annual funding.

The first remedy is to stretch the schedule, and the second is to reduce the scope of the program. You will no doubt find yourselves in this position, and you will receive a great deal of advice from the nonparticipants, but

you should beware of "descoping." A cursory examination of the cost models will show that in the manned programs, only 20 cents of every dollar go to hardware. (In the unmanned programs, the number is closer to 40 cents.) Once the management structure is in place and the contracts have been awarded, virtually all of the other costs are fixed or very difficult to reduce. Take out all the content and the program cost will still be 80 percent of the estimate! The lesson is that if you are forced to remove content, you should be sure to take out every cent that is associated with that content: prime wraps, nonprime wraps, test beds, personnel, and, if necessary, the kitchen sink. It will be difficult to find, but it will be worth the effort.

If this were a mystery novel, it might well be called "The Case of the Missing 80 Percent." Where does it all go, and why is it only 60 percent for unmanned programs? Much of this is valid and accounts for systems engineering and integration at all levels of the program, including test and evaluation, operations, and many other things. But it also accounts for duplication of test facilities, overlaps between assignments, management style, inefficiencies and a host of hidden costs associated with maintaining the institutions that are often invisible to the program manager. The systems engineer is responsible for ferreting out the good from the bad. It is a simple fact that the first one percent reduction in these wraps (80 percent to 79 percent) increases the amount of hardware by five percent (20 percent to 21 percent)! A 20 percent improvement in the wraps (80 percent to 60 percent) results in a doubling of the hardware (20 percent to 40 percent) or cutting the program costs in half for the same amount of hardware! "Thar's gold in them thar hills."

The UPN System. The NASA budget is prepared and submitted using a system of breakdowns known as the unique project number (UPN) system. All parts of the

Agency are required to report their annual needs on the basis of this system, including the program offices. From a program point of view, a fatal flaw in this process is the numbering system, which generally describes functions rather than end items and is therefore not in consonance with the principles of a WBS system.

It is essential that the program manager be able to trace the equivalence of the UPN number and its corresponding WBS element. This will require a joint effort between systems engineering and the program control people. Without this traceability matrix, the program manager will not know what is being asked for or where the money is going. Too often the UPN number is perceived as directly equivalent to the WBS element, but this is very seldom the case unless the WBS is not end-item oriented. (The latter happens more often than it should.) One way to avoid this situation is to make the annual budget call for the program using the WBS system and then translate it to the UPN system for the purpose of aggregating the total NASA budget. I have never seen this happen.

The Cost of Operations. I mentioned earlier that the costs of operations are now about 50 percent of the NASA budget. This is partly due to the increase in the operational life of a program and to the fact that we have not learned to design systems for operability. It has not been necessary in the past. It is also true that the productivity of the operations infrastructure has not been high on the program manager's list. If we are to reduce total program costs, which are vital to the Agency and to the program, it is time to strike a new level of cooperation between these two normally separate parts. The program and the systems engineer must assume a large part of the responsibility.

The Institution and the Program

Although not directly related to the systems engineering process, a number of things bear

directly on the program and have a major effect on the ability to perform the various program functions. These generally concern the relationship between the program and the institution. NASA was originally established using the resources of the National Advisory Committee for Aeronautics, known as NACA, an aeronautical research organization that was seldom involved in large development programs. The budget was relatively small, and there were few contractors. In fact, all contracts were signed at the Washington office, the NACA equivalent of Headquarters.

It quickly became apparent that, in addition to the research centers, a development center was needed. Goddard Space Flight Center (GSFC) was established to perform this function. This was rapidly followed by the Lyndon B. Johnson Space Center (JSC) in Houston, the George C. Marshall Space Flight Center (MSFC) in Huntsville, and the Jet Propulsion Laboratory (JPL) in Pasadena. Almost immediately, GSFC and JPL became responsible for multiple unmanned programs, which were largely contained within a single Center, and JSC and MSFC became responsible for multi-center manned programs. In both cases, program offices were established and the Centers provided the resources, both personnel and facilities, to support the program.

With the exception of JPL, which is a Federally funded research and development center and operates outside the civil service system, all NASA personnel and basic facilities are funded separately from the programs in line items known as Research and Program Management (RPM) and Construction of Facilities (CoF). Program-specific facilities are funded by the program and these facilities are most often operated by support contractors, also funded by the program. This system was established so that the programs would be managed by government personnel who would rotate from program to program

and carry their experience with them. This worked very well until the late 1960s when the budget began to fall rapidly, and there was a significant reduction in NASA personnel.

By the early seventies, both the budget and the number of personnel had been cut in half, but the number of Centers remained essentially the same. The cost of maintaining the institution could no longer be sustained by the RPM and CoF line items. The solution was to tax the programs based on the number of personnel that were applied to the program. Unfortunately, the program manager does not decide how many people should work on the program, which, by tradition, is the responsibility of the Center director. Neither does the program manager participate in determining the level of the tax. These decisions, again by tradition, are made by the comptroller.

Maintaining the Institution

Unless the basic system of funding personnel is changed, the programs will most certainly be responsible for funding some of the institutional costs that are not related to the program; the RPM budget will never be allowed to grow to compensate for this. The question is rather how large the institution needs to be to support the program and how that decision is made. I mentioned earlier that the WBS should represent the totality of the program and should always describe deliverables; this problem runs counter to that principle. I believe that the solution lies in accepting this cost for what it is, negotiating the level of tax with the program manager for the duration of the program, and taking it off the top each year. It may not be controllable in the normal sense, but at least it is a known number.

Personally, I believe that the Agency would be better served if the development centers were managed using an industrial funding system similar to JPL and many other gov-

ernment facilities, including the Navy labs. But until that happens, it will be necessary to find some balance between the institutional and program needs.

Management Stability

Every program will change management during its life cycle. The common practice in NASA has been to make these changes deliberately between phases. It is not uncommon to see as many as four different managers during a program, including a specialist in closing off completed programs. The positive side to this is that it is possible to match the needs of each phase of a program to the special capabilities within the Agency. The negative side is that each manager has a different style, each program has different management needs, and often these do not match when the changeover occurs between phases. One way is not always right and another always wrong, but each is different, and changes even in management style can, and usually do, increase the cost of the program. The secret then is to stick with a team as long as possible, particularly the systems engineering team, something that is easy to say and difficult to do in these times of declining internal expertise and increasing retirements.

The Tyranny of Experience

Too often, you will find resistance to change in the way things are done. "We have always been successful (measured by performance) doing it this way, and it's very dangerous to change winning ways." "If it ain't broke, don't fix it." "You get no credit for an on-time failure." All true and at the same time, destructive to valid new ways of doing business, especially when it comes to introducing more efficient or less expensive ways. When the space program started, we had no experience and what followed was the most innovative and exciting period in the history of high technology programs. But now we have all that experience, and it has become a burden. By all means, you should keep the wise

heads around (they may still save you), but take advantage of the explosion in new technologies and capabilities, which allows for things that we could only dream of 30 years ago. You should be careful before you introduce a change, but you should not dismiss it out of hand.

Does It Matter?

We have been in the civilian space business for almost 40 years, and time after time we have shown that we can rise to any challenge and lead the competition, provided we have the resources. Time and time again the Federal Government has provided the resources. We have been the envy of the world. We have written the book on the subject, both from a technical and a management sense.

Until now, it was enough to know that we were the best. There was no established competition, most of the money was spent internally, and cost efficiency was second to performance. Some have characterized it as a Works Projects Administration (WPA) for the technologists! The problem is that in this era of budget deficits and trade deficits, there is not enough discretionary money to go around. Even without international competition, it would be imperative to get more out of our research dollars. The trouble is that we have learned profligate ways, as neither the government nor the contractors give rewards for cost efficiency. While we were

basking in this glory, the rest of the world has been catching up; they have read the book. The competition, supported by their governments, is getting good and fierce.

But there is a difference; the competition believes that the space business is here to stay. I said space business, but I meant commerce, and in commerce cost efficiency is paramount. Do we still want to stay at the top, or are we ready to leave it to the rest of the world? Are we prepared to do what is necessary to stay in the game? After all, it's only a space program. Does it matter? You bet!

Can Anything Be Done?

In this paper, I have attempted to show where cost fits into the space program's engineering and management business. A combination of things have placed cost at the bottom of the priority ladder except in matters of the inexorable annual budget. There are many ways to improve cost efficiency, some of which are available to the program manager. In the long run, it will take a concerted effort by all of us to make a difference. The Executive branch and Congress, together with industry and academia, must work as before, when we perceived that we were second. In the meantime, I hope that I have been able to give the budding systems engineer and program manager a few tips to do something about the problem of cost considerations. We can only do something about it if we want to!